

A study on the use of the PACS bolometer arrays for submillimeter ground-based telescopes

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ABSTRACT

A new kind of bolometric architecture has been successfully developed for the PACS photometer onboard the Herschel submillimeter observatory. These new generation CCD-like arrays are buttable and enable the conception of large fully sampled focal planes. We present a feasibility study of the adaptation of these bolometer arrays to ground-based submillimeter telescopes. We have developed an electro-thermal numerical model to simulate the performances of the bolometers under specific ground-based conditions (different wavelengths and background powers for example). This simulation permits to determine the optimal parameters for each condition and shows that the bolometers can be background limited in each transmission window between 200 and 450 microns. We also present a new optical system that enables to have a maximum absorption of the bolometer in each atmospheric windows. The description of this system and measurements are showed.

Keywords: Large bolometer array, ground-based telescopes, submillimeter astronomy, simulations, submillimetric absorption, thin dielectric layers.

1. INTRODUCTION - CEA BOLOMETERS.

CEA has now a strong experience in the domain of large bolometer arrays for submillimeter astronomy. In 1997, LETI/LIR and DAPNIA/Sap have started to develop new technology bolometers to meet the requirements of the HERSCHEL Space Observatory (see G.L. Pilbratt, this conference vol. 6265) : how to build a wild-field submillimetric camera with fast mapping capability and a very good sensitivity in a relatively high background power environment?

The original approach was to use different known technologies, many of them developed during the ISOCAM project at CEA (Ref. [1]), and put them together to build a new kind of bolometer array. Such technologies include ionic implantation (for resistive thermometers), silicon micro-machining, flipchip technology using indium bumps for bonding the different elements and low temperature CMOS amplification. It was also decided not to use Winston cones, but rather a "resonant metallic absorption" system.

That led to the conception of a non traditionnal bolometric detection system, more similar to the CCD concepts used in other domains of astrophysics. 256 pixels compose the basic array, each pixel having a $0.5F\lambda$ field of view to fully sample the image in the focal plane (see F. Simoens et al., this volume). Pixels contain two semiconducting thermometers (silicon made with phosphorus implantation and boron compensation) which work at 300 mK in the "hopping conduction" regime. The submillimeter light absorption is obtained with a quarter wave cavity. The bottom of the cavity is a silicon layer coated with a thin gold layer that acts as a reflector (more details in section 3). Indium bumps support the upper absorbing layer made of silicon which is metal coated (TiN, superconductive at 300 mK but absorbing for submillimeter frequencies). This layer has a grid-like geometry to reduce the heat capacity of the bolometer.

The signal is read out at the middle point of the resistor bridge and is processed by CMOS transistors. Because of the intrinsic noise of CMOS followers, the impedances of the bolometer resistors have to be very high (a few $G\Omega$) in order to provide a very high response. A cold (2K) CMOS multiplexing system (16 to 1) is located

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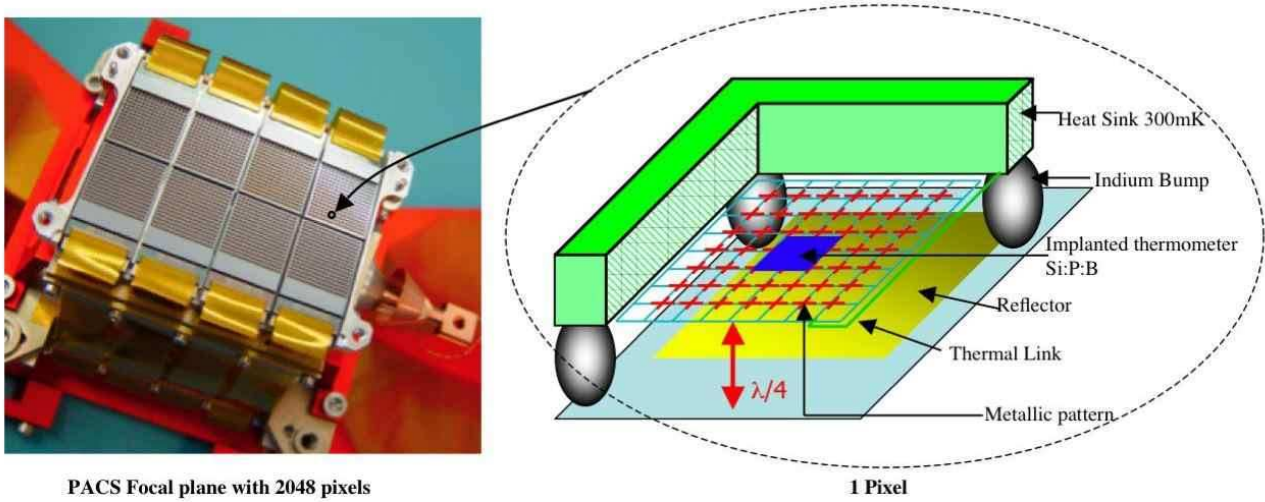


Figure 1. The picture on the left shows a pre-version of the 100 μm focal plane of the HERSCHEL PACS photometer. It is made of 8 subarrays each containing 256 bolometers. The sketch on the right side describes one of these pixels. A first electronic stage (impedance reduction) is located below the quarter wave cavity reflector, at 300 mK. CMOS transistors at 2K located a few cm below the pixels perform the multiplexing.

below the detection stage. These bolometer arrays can be butted end to end to form very large focal planes (see figure 1).

CEA has built two bolometric focal planes for the PACS photometer on HERSCHEL (see N. Billot et al., vol. 6265 this conference). Flight models are being tested and calibrated. The detectors fulfill all the requirements in particular in terms of sensitivity (BLIP* conditions), bandwidth (electrical and thermal) and $1/f$ noise suppression.

Since 2000, we have started to work on the ways to adapt these bolometer arrays to ground-based submillimeter telescopes. Indeed, this now well-mature bolometer technology seems very well suited for ground-based conditions, like high and variable background power on the focal plane or large field of view coverage. Recent developments are presented in the following sections.

2. ELECTRO-THERMAL MODEL

2.1. Description

In order to estimate the best performances for our bolometers, we have developed a numerical and dynamical model which permits to obtain optimum values of different parameters (such as bias, or thermal conductance for example) in different observing conditions. The model is based on the general differential equation that manages thermal exchanges in the bolometer (see Ref. [2]) :

$$P_{ph} + P_J = C \frac{dT_b}{dt} + \overline{G_{th}}(T_b - T_0) \quad (1)$$

with P_{ph} = total photonic power incident on one pixel, P_J = electrical power coming from the bias of the resistive element in the bolometer, C = total heat capacity of the pixel, T_b = bolometer temperature, T_0 = heat sink temperature, constant at 300 mK, $\overline{G_{th}}$ = average value of the thermal conductance between T_b and T_0 , and t = time.

Solving this equation permits to get the temperature of the bolometer as a function of time (see figure 2). All the other parameters depend on this temperature :

*BLIP : Background Limited Performances

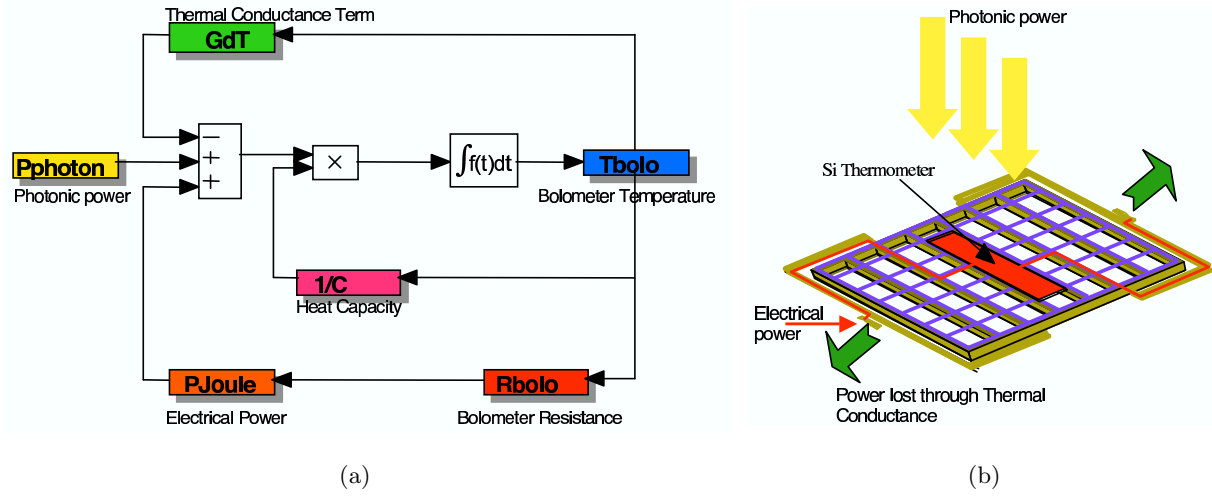


Figure 2. (a) Principle of the electro-thermal dynamical model used to simulate the bolometer behaviour. It is based on the power balance inside the bolometer and includes specific parameters such as heat capacity, thermal conductance and empiric relations for the resistor behaviour. (b) Schematic representation of the different powers involved in the bolometric detection.

- Bolometer impedance (empirically adapted from Efros Law, ref.[3]) :

$$R = R_0 \exp \left(\sqrt{\frac{T_0}{T}} \right) \exp \left(-\frac{qL_{(T)}E}{kT} \right) \quad (2)$$

where R_0 and T_0 are constants characterising the type of resistor we are using (Silicon type with implanted Phosphorus and Boron compensation), $L_{(T)}$ is the hopping length and E is the electric field inside the resistor.

- Thermal conductance :

$$G(T) = \alpha_1 T + \beta_1 T^3 \quad (3)$$

where the T term characterizes the heat conduction in metals (from Drude theory) and the T^3 term corresponds to a dielectric conduction (Casimir model).

- Heat capacity :

$$C(T) = \alpha_2 T + \beta_2 T^3 + \gamma_1 \exp \left(\frac{cste}{T} \right) \quad (4)$$

where the T term corresponds to the doped silicon resistor, the T^3 term corresponds to the dielectric (silicon grid) and the exponential term is a characteristics of the absorbing metal (TiN).

All the constant terms and empiric laws for these parameters have been determined experimentally. The model itself has been created using MATLAB[†] and its extension SIMULINK. We use this simulation to determine what would be the best performances of our bolometers in ground-based conditions.

[†]MATLAB is a mathematical software from *The MathWorks* Company

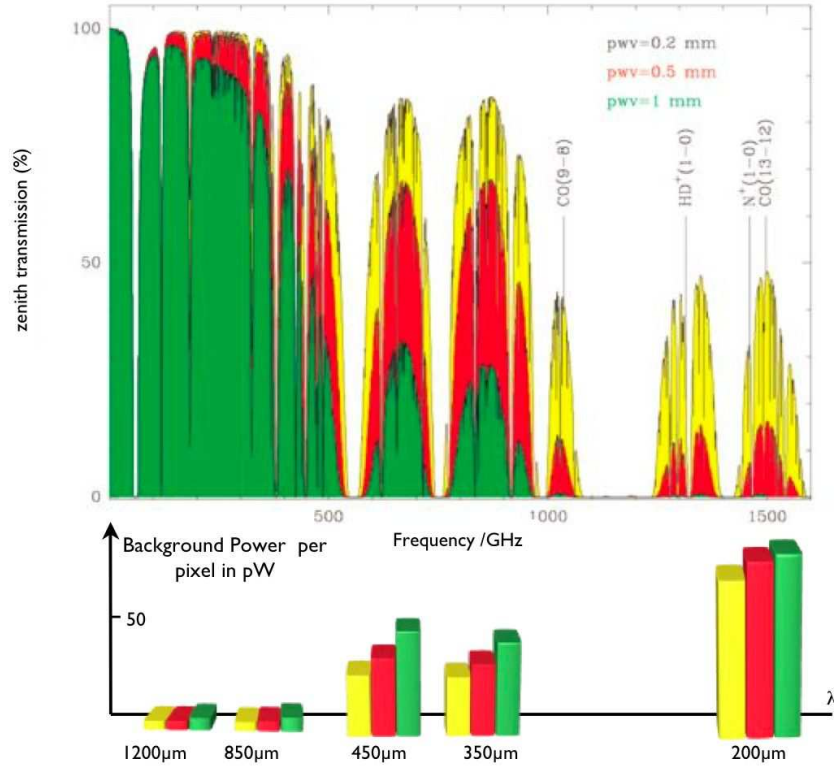


Figure 3. The different atmospheric transmission windows in the submillimeter regime on the Chajnantor site in the Atacama desert. The colors correspond to different values of precipitable water vapour contents (adapted from [4]). The bottom part shows the estimated background power falling on one pixel, mainly coming from the atmosphere and the telescope.

2.2. Atmospheric Bands

Only a few sites on Earth are suitable for submillimeter astronomy between 200 and 865 μm . The Chajnantor plateau in the Atacama desert for example provides very good conditions, even for the shortest wavelengths. Figure 3 shows the typical atmospheric transmission curves on that site for different amounts of precipitable water vapour. We have investigated the behaviour of our bolometers in the main following atmospheric windows: 200 μm , 350 μm , 450 μm , 865 μm and 1.2 mm considering a 12m diameter telescope on a site like Chajnantor.

For each of these bands, we have estimated the background power incoming on one pixel. The total background power, P_{pix} , is calculated by :

$$P_{pix} = E\eta_{pix}\eta_{abs} (P_{opt} + P_{tel} + P_{sky}) \quad (5)$$

where E = throughput of the system, η_{pix} = geometric filling factor of a pixel, η_{abs} = absorption coefficient of the pixel, P_{opt} = power emitted by the cold internal optics of the camera, P_{tel} = power emitted by the telescope and P_{sky} = power coming from the atmosphere (depends on opacity). Typical values of background power are shown in figure 3 and table 1.

2.3. Results of Simulations

One of the possible ways to use the numerical model is to determine the optimum voltage of the bolometer which gives the best sensitivity. To estimate it, we add to the constant optical background a very small low frequency power component and see how the output parameters evolve when increasing the voltage bias. Amongst these

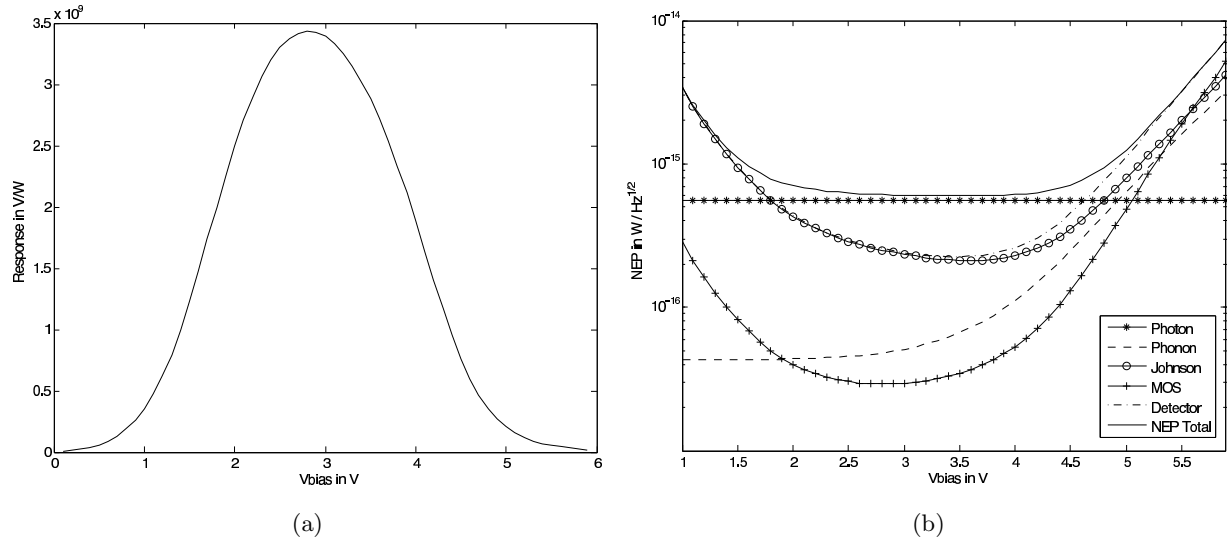


Figure 4. (a) Simulated electro-optical response of the bolometer vs resistor bridge voltage, in the case of a power background corresponding to the 200 μm atmospheric window. (b) Simulated NEP as function of the bias in the same background conditions. The optimum bias corresponding to the minimum detector NEP is in that case 3.5 V.

output parameters, we use the NEP (Noise Equivalent Power) as a figure of merit for the bolometer sensitivity, and also the electro-optical response, in Volt per Watt.

The figure 4b shows the typical NEP curves as functions of the bolometer voltage, in the case of a use in the 200 μm window. We can see also that the electro-optical response of the bolometer (figure 4a) reaches a maximum for almost the same value of bias. This curves shapes can be explained by the following :

- (a) before the optimum bias point, the electro-optical response increases with the voltage bias, as for a normal resistor behaviour. The bolometer temperature increases slightly, which in return decreases the resistance of the bolometer. This effect decreases the noise associated to the bolometer resistor (Johnson noise).
- (b) after the optimum bias point, even if the thermal conductance increases, it is not sufficient enough to evacuate all the accumulated heat (the heat capacity also depends on the temperature). There is a thermal runaway due to the rapid increase of the bolometer temperature which produces a rapide degradation of the performances.

For each atmospheric window, we are therefore able to determine the optimum bias that leads to the best NEP. Note that, we also tried to optimize the value of the thermal conductance and found that the best performances are obtained for a small change of the value compared to the one used for PACS ($\overline{G_{th}}$ increased by a factor of 1.2).

The figure 5 shows the different NEP in each atmospheric band. It shows that for the three shorter wavelengths bands (200, 350 and 450 μm) the performances are clearly limited by the background. It means that we could use a single bolometer to get BLIP conditions in these three bands. The 865 μm and 1.2 mm bands would need another type of bolometer, with a thermal conductance more adapted to the lower background conditions.

Table 1 gives the estimated NEP and NEFD for each considered atmospheric band. The NEFD (Noise Equivalent Flux Density) is an estimation of the instrument sensitivity during an astronomical observation. It is equivalent to the flux of an object that is detected with a Signal / Noise = 1 in 1s of integration and is related

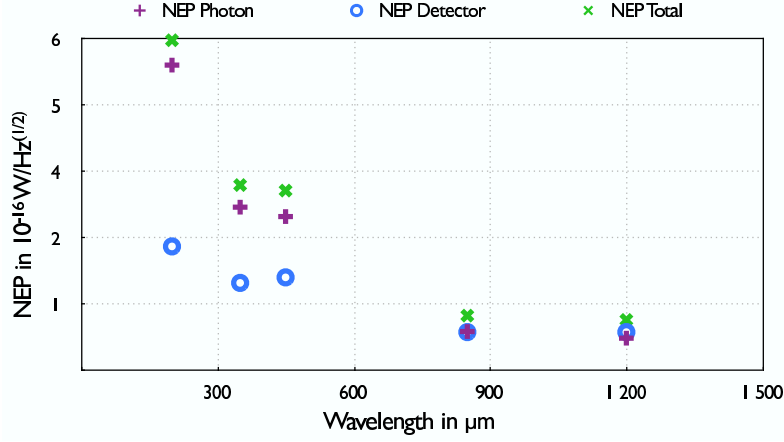


Figure 5. Estimated values of the minimum NEP for the 5 atmospheric windows considered earlier.

to the telescope diameter, the optics transmission and the atmospheric conditions. In the table, it is given for the usual 5σ , 1 hour integration conditions. At $200 \mu\text{m}$, this (point) source detection limit is about 28 mJy. For comparison, the PACS sensitivity will be about 3 mJy. The big advantage of such a ground-based instrument over a space mission is of course its angular resolution, which in a case of a 12m diameter telescope would be ~ 4 arcsec at $200 \mu\text{m}$ (~ 13 arcsec for PACS). Because of the existing possibility to join the arrays, it would be possible to build the same kind of focal plane as the ones found in PACS, (32×64 pixels), to cover relatively large fields of view in all the bands.

Wavelength in μm	200	350	450	850	1200
Average Window Transmission	50%	65%	65%	85%	90%
Typical Background per pixel in pW	70	35	40	5	5
Beam FWHM in arcsec	4	7.5	9.5	18	25
Field of View (for a 32×64 array)	$0.9' \times 1.8'$	$1.6' \times 3.2'$	$2.1' \times 4.2'$	$3.9' \times 7.8'$	$5.5' \times 11'$
NEP Photon in $\text{W}/\text{Hz}^{1/2}$	5.5×10^{-16}	2.9×10^{-16}	2.8×10^{-16}	0.7×10^{-16}	0.6×10^{-16}
NEP Detector in $\text{W}/\text{Hz}^{1/2}$	2.2×10^{-16}	1.6×10^{-16}	1.7×10^{-16}	0.7×10^{-16}	0.7×10^{-16}
NEP Total in $\text{W}/\text{Hz}^{1/2}$	6.0×10^{-16}	3.3×10^{-16}	3.3×10^{-16}	1.2×10^{-16}	1.1×10^{-16}
NEFD in mJy (5σ , 1h)	28	9	5	3	1.5

Table 1. Estimated performances of the bolometers in the different atmospheric windows.

3. ABSORPTION SYSTEM

3.1. Problem and Solution

Our bolometers use a resonant cavity to absorb submillimeter waves. It is based on a principle which is known for a long time (see [5]). When an absorbing material[‡] is placed at a distance $\lambda/4$ over a reflecting layer, it is in theory possible to absorb 100% of the energy at this particular wavelength λ . To extend the absorption profile, we use specific metallic patterns like crosses or loops (horizontal resonance, see figure 6a).

In our design, we use indium bumps to tune the cavity height to the desired wavelength we want to detect. These bumps are also used as electrical links between the silicon grid (containing the resistors) and the reflector layer where we find the first stage of signal processing.

[‡]We use a TiN alloy as the absorber because it is compatible with the manufacture processes and superconductive at 300mK but absorbing for submillimeter waves.

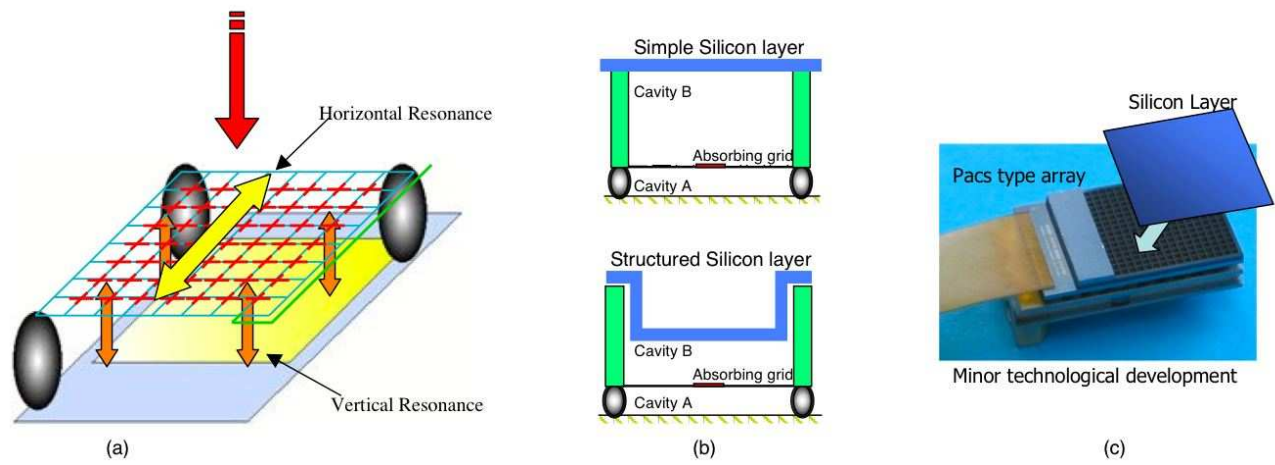


Figure 6. (a) Schematic representation of the "double resonance" absorption system of one pixel. (b) Representations of two solutions to tune the absorption of the bolometer to different atmospheric windows. (c) In practice, these solutions consist in adding a thin dielectric layer (for example silicon) on the top of an existing PACS type array.

With our current manufacturing methods, there is a limitation in the size of these indium bumps, around $35\ \mu\text{m}$ (PACS uses two types of cavities, at 20 and $25\ \mu\text{m}$, adapted respectively to detection at $100\ \mu\text{m}$ and $180\ \mu\text{m}$). Even with the help of the metallic patterns, it is not possible to have a very good absorption in bands over $300\ \mu\text{m}$ (see figure 8a).

In 2000, we started to study different technological possibilities to overcome this problem. One possible solution is to add a dielectric layer on the front side of the bolometers. When optimizing the thickness of this layer, it acts as an antireflective system, which reduces absorption at certain wavelengths and enhances it at others. It also has the great advantage of keeping the existing PACS type bolometers design by only adding a dielectric layer on the front side of it. We have chosen silicon as the antireflective material. The layer can be either flat or structured, in order that we can tune the second cavity to different heights (noted B in figure 6b).

To modelise the absorption, we have developed a 1D approach of this optical system, based on thin layers formalism. One way to describe the light behaviour in a stack of dielectric layers is to use an algorithm based on "characteristic matrix". Each layer in the stack is modelised by a 2×2 matrix which describes how the electric field varies between the two sides of a particular dielectric layer. If we know the electric field at the entrance, it is therefore possible to predict it at the exit of the stack, by simply multiplying the matrixes. It is then possible to get access to the transmission and reflexion coefficients.

In our case, each layer[§] is modelised by such a matrix. We then vary free parameters like the thickness of the silicon antireflective layer and the height of the cavity B to find solutions where the reflection coefficient of the stack would be zero, for a given optical bandwidth. The figure 7a presents a diagram where contours show the absorption coefficient when the thickness of the silicon layer varies. Many solutions exist for a given wavelength, and they are chosen relatively to their technical feasibility.

3.2. Results

To test the performances of this concept, we have decided to use an existing PACS array (figure 6c) originally adapted to the $[130 - 210]\ \mu\text{m}$ PACS band (cavity A of $25\ \mu\text{m}$) and which has been modified in order to get a high absorption coefficient in the $450\ \mu\text{m}$ atmospheric band. In figure 7a, one possible solution is to use a plane silicon layer with a thickness of $148\ \mu\text{m}$, glued on the top of the array.

[§]In our model, we consider the following layers : silicon(antireflective), cavity B, absorber, silicon grid, cavity A and reflector.

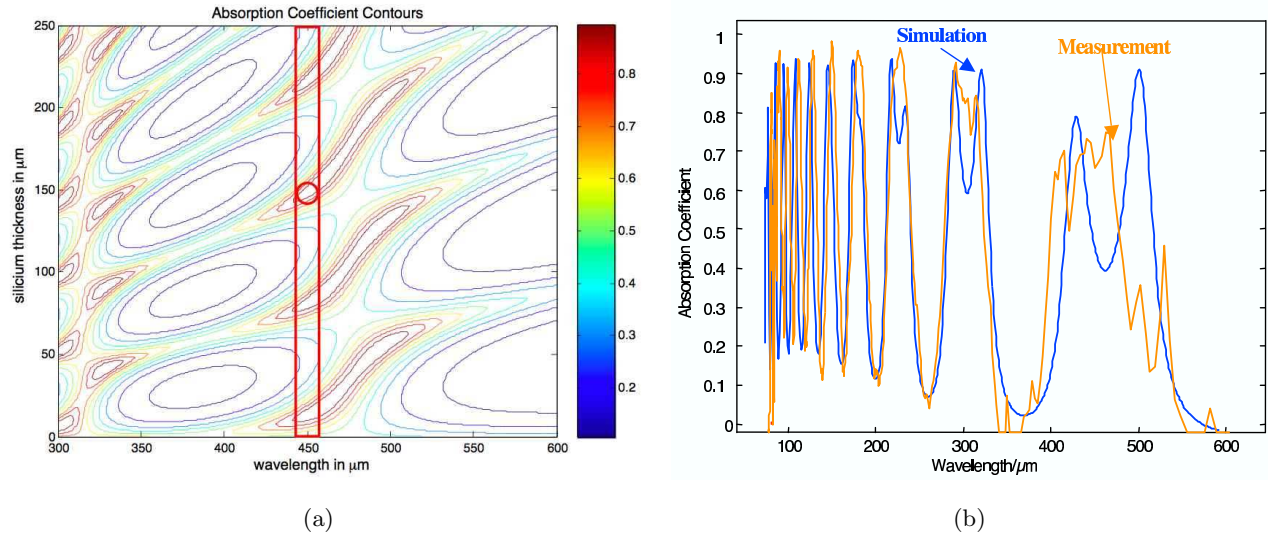


Figure 7. (a) Diagram showing the absorption coefficient contours of a bolometer as a function of the wavelength and the thickness of the dielectric layer. The red circle shows a possible solution for a maximum absorption at 450 μm (silicon layer of 148 μm). (b) Experimental verification of the predicted absorption profile in the case of plane silicon layer of 148 μm .

Figure 7b displays the expected profile and shows indeed an absorption peak around the 450 μm central wavelength. A cold Martin-Puplett Fourier Transform Spectrometer[¶] has been used to verify experimentally this absorption curve. The experimental curve in figure 7b shows a very good correspondance to the expected simulated profile^{||}, which gives a lot of credit to this new method.

Using this one dimension approach, we tried to find solutions to adapt a PACS array to the other submillimeter atmospheric bands. We found that, when adding a 59 μm silicon layer at a distance of 175 μm above the absorbing grid, the bolometer can be simultaneously sensitive to the three bands at 200, 350 and 450 μm . This is a very interesting feature, because we can imagine building a single focal plane instrument which could be background limited in the three bands, using different passband optical filters. Solutions exist for adapting the arrays to the 850 μm and 1.2 mm bands, but give less efficient results in terms of absorption, due to the size limitation of the quarter-wave cavity.

To build this particular "three bands" array, the lower cost solution consists in etching a structured silicon layer which will be embedded inside each pixel^{**}. Tests have been made at CEA/LETI, using RIE etching on double SOI (Silicon On Insulator) substrates and have successfully demonstrated the feasibility of this technique.

4. CONCLUSIONS

CEA is now developing bolometer arrays for ground-based applications, thanks to all the experience gained with the development of the PACS bolometers. A specific program, called ARTEMIS is totally dedicated to that issue (see M. Talvard et al., this volume). Simulations and laboratory work have already started and first results

[¶]A Martin-Puplett Fourier Transform Spectrometer is a particular type of Michelson interferometer, in which the beam splitter is a polarizing grid. It is well suited for studies over broad bands in submillimeter domain, because the polarization properties remain constant.

^{||}Other types of models have been used to verify this kind of design, like 3D electro-magnetic modelling with HFSS, done at CEA/LETI.

^{**}The inter-pixel silicon walls are 450 μm high and can not be reduced in size at low cost. That justifies the use of a structured antireflective silicon layer.

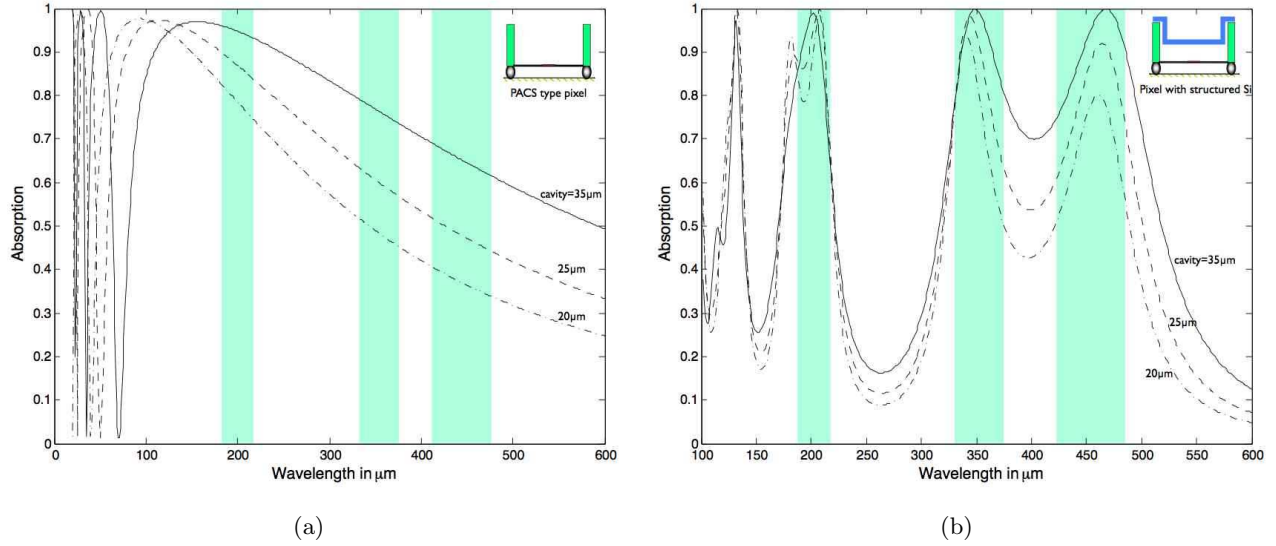


Figure 8. (a) Simulated absorption curves when using a PACS bolometer, for three cases of cavity thickness. (b) When using a structured silicon layer of 59 μm , a bolometer can have simultaneously a maximum absorption coefficient in the three atmospheric bands at 200, 350 and 450 μm .

show that it is possible to use the PACS arrays for atmospheric bands between 200 and 450 μm with very small adjustments (thermal conductance). We show that the bolometers can be background limited in all these bands. The other interesting result concerns a new absorption system that makes possible for a single array to be used in all the three bands. Tests on ground-based telescope have started, with such modified arrays and show promising results.

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